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CHANGES IN HEART-RATE, BLOOD-PRESSURE, AND DURATION OF SYSTOLE RESULTING FROM BICYCLING.

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I. INTRODUCTION.

IT is well known that muscular work has a marked influence on the action of the heart and the arterial tension. Under certain conditions this influence is normal, healthful, and invigorating; under other conditions, which we have not yet learned to distinguish clearly, it may result in serious injury, — permanent dilatation, valvular incompetence, and even rupture of the heart wall having been known to follow from violent exertion. It is, therefore, of the utmost importance to physical education that extensive and careful studies should be made with a view to discovering more fully how the circulatory system is affected by muscular work of different kinds and degrees of intensity under various conditions. Furthermore, since we do not know at what stage of muscular work these various influences are at a maximum, it is not sufficient to note the after-effects, but the changes in heart-rate, blood-pressure, etc., must be followed from minute to minute as long as the influence of the work continues.

In a previous research the writer made such a study of the changes in pulse-rate accompanying and following several kinds of work.[1] Since forms of work in which the pulse can be recorded continuously

[1] BOWEN: Contributions to medical research. University of Michigan, 1903, p. 462.

are also favorable for the determination of blood-pressure, this research has been extended with the object of ascertaining the relative intensity of the changes in pulse-rate and blood-pressure which occur during moderate exercises of speed, as exemplified by bicycling. A number of the experiments were also utilized for further study of some changes in duration of systole which the writer had observed in previous work. The experiments were made in the Physiological Laboratory of the University of Michigan between January 1 and August 15, 1903. A study of the changes in quantity of respired air and in the output of carbon dioxide during work, made in company with Mr. G. O. Higley of the Department of Chemistry, will be published soon.

II. Previous Work.

In the decade between 1890 and 1900 there were several extensive studies of the after-effects of muscular work upon the pulse,[1] but studies of the heart-rate during the progress of muscular work date from 1900. During that year there were three researches upon the subject: one in Vienna by Grünbaum and Amson;[2] one in Dorpat, Russia, by Dehio;[3] and one in Ann Arbor by the present writer. Grünbaum and Amson counted the subject's pulse with the aid of a stop-watch during work on several gymnastic machines and a bicycle; Dehio counted the pulse while the subject, lying horizontally on his back, lifted a weight attached to the foot; in my work, a graphic record of the pulse was taken during work upon a bicycle and a foot-power lathe, and also while tapping a Morse key.

Grünbaum and Amson looked for the general course of the changes in pulse-rate during and after the work, and tried to correlate the extent of these changes with the amount of external work done. Dehio studied the difference in the effects of work upon persons of different ages, and found a greater acceleration of the pulse in the younger subjects. I studied the same points covered by Grünbaum and Amson, and also gave special attention to the latent period.

The study of blood-pressure during work was made first upon the horse: originally by Marey,[4] and afterward by Kaufmann,[5] and by

[1] See my former article for bibliography of this work.

[2] Grünbaum and Amson: Deutsches Archiv für klinische Medicin, 1901, lxxi, p. 539.

[3] Dehio: St. Petersburger medicinische Wochenschrift, 1901, p. 79.

[4] Marey: Physiologie médicale du sang, Paris, 1863.

[5] Kaufmann: Archives de physiologie, 1892, p. 279.

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Zuntz and Hagermann.[1] These writers agree that in the horse the arterial pressure falls as soon as the animal begins to walk or trot. Tangl and Zuntz[2] found that in case of the dog a rise of pressure occurs when work begins.

The after-effect of muscular work upon blood-pressure in man, has been studied by a great many observers, among whom may be mentioned Hill,[3] Edgecumbe and Bain,[4] Maximowitch and Rieder,[5] Kornfeld,[6] and McCurdy. All of these writers report an increased arterial pressure immediately after the cessation of work with a return to normal after a variable time depending upon the severity and the duration of the work.

McCurdy[7] was the first to call attention to the necessity of determining the pressure during the progress of the work, and he studied the pressure in man during maximal effort in lifting. Masing[8] has studied the changes in blood-pressure while the subject worked upon the apparatus used by Dehio in studying pulse-rate. Masing found that although work of the type used causes a faster pulse-rate in the young, it causes a higher blood-pressure in older persons. Moritz[9] made a similar study, comparing the effects of work in sound men and men suffering from heart diseases.

The duration of systole has been studied by Thurston,[10] Edgren,[11] Hürthle,[12] Chapman,[13] and others, using graphic records of the pulse as the basis of the determinations. Muscular work was sometimes used by these writers as a means of increasing the pulse-rate, but none of them determined the duration of systole during the work. Chapman assumed that the duration of systole always bears a certain numerical relation to the duration of the entire cycle, and constructed a table based upon this assumption, showing the length of systole for

[1] Zuntz and Hagermann: Stoffwechsel des Pferdes, Berlin, 1898, p. 382.
[2] Tangl and Zuntz: Archiv für die gesammte Physiologie, 1898, lxx, p. 544.
[3] Hill: Schäfer's text-book of physiology, 1900, ii, p. 80.
[4] Edgecombe and Bain: Journal of physiology, 1899, xxiv, p. 48.
[5] Maximowitch and Rieder: Deutsches Archiv für klinische Medicin, 1890, xlvi, p. 329.
[6] Kornfeld: Wiener medicinische Blätter, 1899, p. 631.
[7] McCurdy: This journal, 1901, v, p. 95,
[8] Masing: Deutsches Archiv für klinische Medicin, 1903, lxxiv, p. 253.
[9] Moritz: Deutsches Archiv für klinische Medicin, 1903, lxxvii, p. 339.
[10] Thurston: Journal of anatomy and physiology, 1876, x, p. 494.
[11] Edgren: Skandinavisches Archiv für Physiologie, 1889, i, p. 67.
[12] Hürthle: Archiv für die gesammte Physiologie, 1891, xlix, p. 66.
[13] Chapman: British medical journal, 1894, i, p. 511.

all pulse-rates from 45 to 200. According to this table, the diastolic part of the cycle shortens faster than the systolic, as the pulse-rate quickens, but the systole is always the shorter, even with the highest pulse-rates. This is contradicted by results obtained previously by Thurston, and later by Zuntz and Schumburg,[1] both finding a time when diastole becomes shorter than systole. In my experiments the diastole is uniformly shorter than systole during work when the pulse-rate exceeds 135 per minute (see Fig. 4).

III. Methods.

In order to study the effects of bicycling in the laboratory, a bicycle frame from which the wheels have been removed is fastened firmly in its usual position, and the rear sprocket is mounted on a shaft carrying a heavy fly-wheel. The fly-wheel used in this instance weighs one hundred fifty pounds and is geared to run slightly faster than the crank shaft. The momentum of the fly-wheel carries the pedals past the dead point, so that the work done upon the machine is like riding a wheel on a smooth road. A strip of leather belting drawn against the polished rim of the fly-wheel provides a variable resistance, the tension of the belting being changed at will by changing the amount of weight suspended from its free end. The amount of resistance is greatest at the moment of starting, but during continuous movement this method of applying friction gives a resistance that is practically uniform. The resistance at the pedals which corresponds to any given tension of the belting can be determined approximately by means of a light lever and a spring balance. The lever is fastened to one crank, and the balance fastened to the lever at some distance from the axis which bears a simple relation to the length of the crank. The crank is now turned by pulling upon the balance at right angles to the lever, and the balance is read while the movement is being made. From the figures thus obtained the resistance at the pedals is readily computed.

The pulse is recorded from the carotid artery by means of two tambours connected by a rubber tube of four millimetres bore. The receiving tambour, made from a tin box-cover, is five centimetres broad, and is without the usual membrane. The open side of the tambour is placed against the skin of the neck over the artery and held in place by a U-shaped wire spring, one end of which is attached

[1] Zuntz and Schumburg: Physiologie des Marsches, Berlin, 1901.

to the tambour by a ball and socket joint, and the other end inserted into a rounded block which rests against the opposite side of the neck. The receiving tambour is fifteen millimetres in diameter, and has a light rubber membrane which transmits its movements to the recording surface by a light celluloid lever.

The recording surface consists of a strip of smoked paper 12.5 centimetres wide, and from four to five metres long, made into a loop which passes around two drums, one of which is actuated by clockwork. Above the pulse-curve a pneumograph records the respiratory movements. Below are the records made by three electromagnetic signals: one of these, connected with a fork or pendulum, records the time; another, the revolutions of the bicycle crank; the third, in circuit with a hand-key, is used to indicate when determinations of blood-pressure are made. Fig. 1 shows the general character of the records.

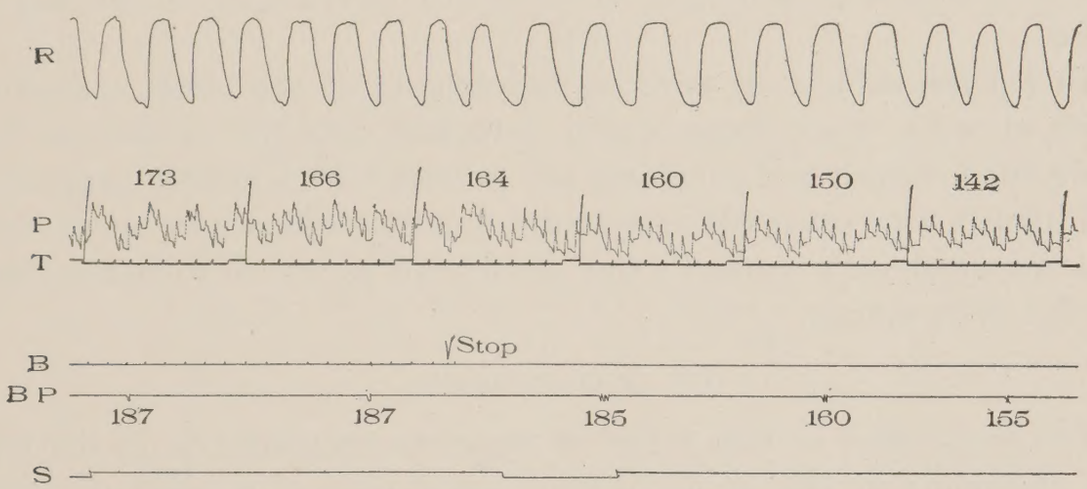

FIGURE 1. — Portion of record taken with slow drums. *R*, respiration; *P*, pulse; *T*, time in seconds; *B*, revolutions of bicycle. *B P*, times at which determinations of blood-pressure were made. The figures written at these points give the pressure in millimetres of mercury. *S*, times at which simultaneous records were taken on quick drum for determination of systole. The part here shown is at the close of a period of work, as indicated by record *B*. Read from left to right.

The duration of systole is determined by recording the pulse along with a fork giving fifty vibrations per second. When this is the only record desired, the outfit just described is used. To determine these small time-intervals accurately the drums carrying the loop of paper must turn rapidly, the entire loop passing the writing points in from one to two minutes. When it is desired to study the duration of systole along with pulse-rate, blood-pressure, etc., during experiments of longer duration, the drums carrying the long loop of paper are turned

slowly, the time being recorded in seconds, and simultaneous records, suitable for determination of systole, are taken on a neighboring drum at any desired intervals. A T-tube is inserted into the rubber tubing connecting the two tambours, and a second piece of tubing leads off from the side branch to a second recording tambour which writes a duplicate pulse-curve for the systole determination.

The blood-pressure is determined by means of the Erlanger sphygmomanometer,[1] with light rubber tubing of one and five-eighths inch diameter for the inner armlet, and a slightly wider strip of sheet brass for the outer one. A wider armlet gives more accurate readings of the absolute pressure, as was first shown by von Recklinghuysen,[2] but one of the width used gives relative pressures with sufficient accuracy and is more convenient. Comparison of readings given with this armlet and a wider one shows that the former gives results from five to fifteen millimetres too high. The pressure determined was the systolic or maximal pressure, as indicated by obliteration of the radial pulse.

To aid the subject in avoiding movements of the neck and arm while at work, since these would interfere with the records to be made, his forehead and shoulders are provided with padded supports, and his left arm, upon which pressure determinations were made, lies in a trough-shaped support; the pedals are provided with toe-clips for the same reason.

IV. Experiments.

The work done in this series of experiments consisted in driving the stationary bicycle at a constant speed against a constant resistance. The speed and resistance chosen were sufficient to cause a marked but not excessive stimulation of the circulation, and to raise the temperature of the body from one to two degrees: in other words, the work done was just vigorous enough to satisfy the needs of a healthy man who is not in training for athletics. The speed used in most cases was one revolution per second; the resistance, 13.3 kilogram; the amount of work done was approximately 400 kilogram-metres per minute. Note was made of the room-temperature and barometer in each experiment, and the temperature of the body was read at frequent intervals throughout most of the experiments.

[1] Erlanger: This journal, 1901–2, vi, p. xxii.

[2] Von Recklinghuysen: Archiv für experimentelle Pathologie, 1901, xlvi, p. 78.

The pulse-rate and blood-pressure were taken before, during, and after thirty different working periods on the bicycle. These working periods were of various lengths, the longest being fifty minutes, and the shortest three minutes. In eighteen of the working periods the duration of systole was determined at intervals of one minute or less, in addition to the other items.

Three men served as subjects: H., a chemist, age forty-five; B., a teacher, age forty; and L., a physician, age twenty-five. All these men were in good health at the time, but none was in "training." B. and L. had been accustomed to athletic work in previous years. Successful records were obtained from H. during thirteen working periods; from B. during eleven, and from L. during six periods.

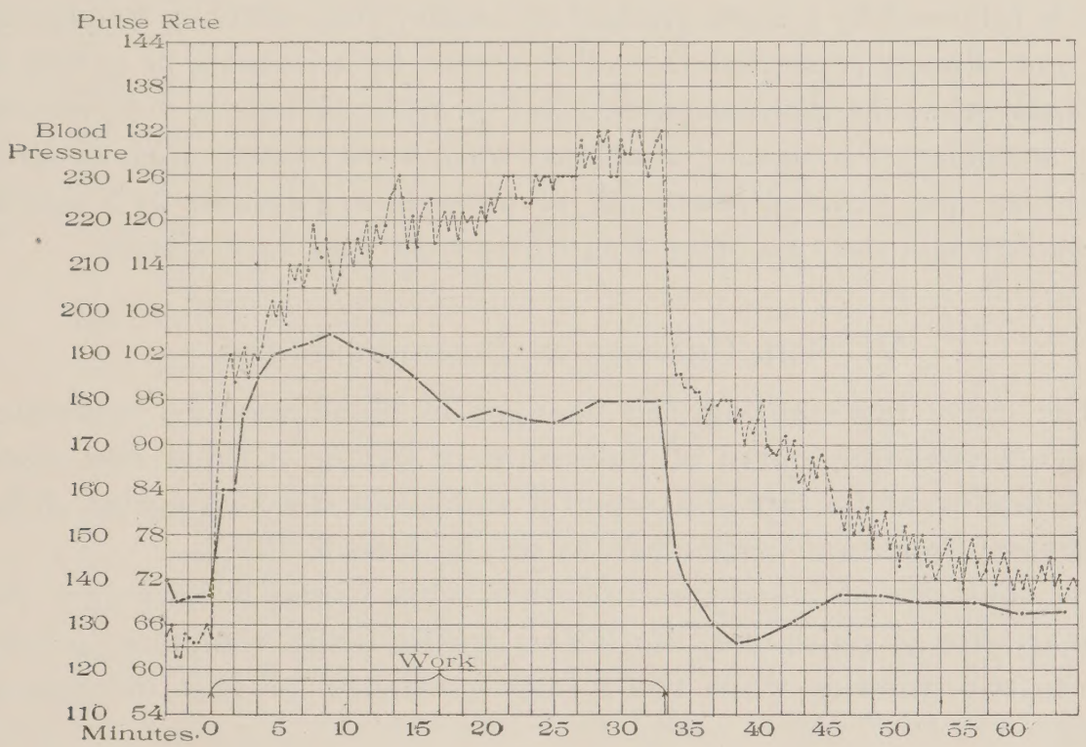

FIGURE 2. — Plotted curves showing relative changes in pulse-rate and blood-pressure during thirty-two minutes of work and the thirty minutes of rest following. *P* (broken line), pulse-rate; *B P* (solid line), blood-pressure. Arrows indicate the time of beginning and stopping the work. Experiment made July 8, 1903. Subject, *H*; speed, one revolution of cranks per second; work, 400 kilogram-metres per minute.

The blood-pressure readings were written on the smoked paper, in the proper place, as fast as they were taken (see Fig. 1). After completing the experiment and fixing the curves, the pulse-rate was counted for each interval of ten seconds, and also written on the paper. Both sets of figures were then plotted as in Fig. 2, — time

being the abscissa in each case, and number of beats per minute and blood-pressure in millimetres of mercury being the ordinates. The readings of body-temperature were also written on the smoked paper as they were taken, and afterwards plotted along with the other items, but as we are not fully satisfied with the methods tried, this part of the investigation will be left until a later paper.

V. The Changes in Pulse-Rate.

With regard to the changes in pulse-rate, these experiments corroborate the results of my previous study in every particular. We have in every instance a sudden and rapid primary rise of pulse-rate when the subject begins to work, and unless the work is very light, this is followed by a more gradual secondary rise, which is frequently but not always separated from the former by a plateau, or period of uniform rate. In the case plotted in Fig. 2, the plateau is not present. The secondary rise usually continues until work ceases; then we have a sudden and rapid primary fall of pulse-rate, followed by a slower secondary fall, the two being frequently separated by a plateau.

VI. The Changes in Blood-Pressure.

The curve representing the changes in blood-pressure resembles the corresponding curve of pulse-rate in having a rapid rise when work begins, and a rapid fall when it stops, but the two curves differ in several important particulars, as can be seen in Fig. 2.

(1) The rise of blood-pressure when work begins follows after the primary rise of pulse-rate, the latter usually being complete in from one to two minutes, while the former continues for four minutes or more.

(2) Instead of rising continuously during the working period, like the pulse-rate, the blood-pressure reaches a maximum after a few minutes, and then declines slowly, with some oscillations, during the remainder of the work. This significant difference in the two curves is of course to be seen only when the work is continued for fifteen minutes or more. The greatest decline observed during a working period was thirty-five millimetres of mercury; in a few instances it was so slight as to be scarcely noticed.

(3) The fall of blood-pressure when work ceases is more rapid than the rise when work begins, but not so rapid as the primary fall of pulse-rate which it accompanies. The rapid fall of pressure, how-

ever, continues to a normal or subnormal figure without interruption, while the primary fall of pulse-rate soon merges into a plateau or a slower secondary fall at some distance above normal. When the pressure becomes subnormal at this time it soon begins to rise again slowly, although the pulse-rate is falling.

VII. The Duration of Systole.

In a former paper I called attention to the fact that the quickening of the pulse when work begins is accompanied by a lengthening of systole, — the quickening being entirely due to a shortening of the

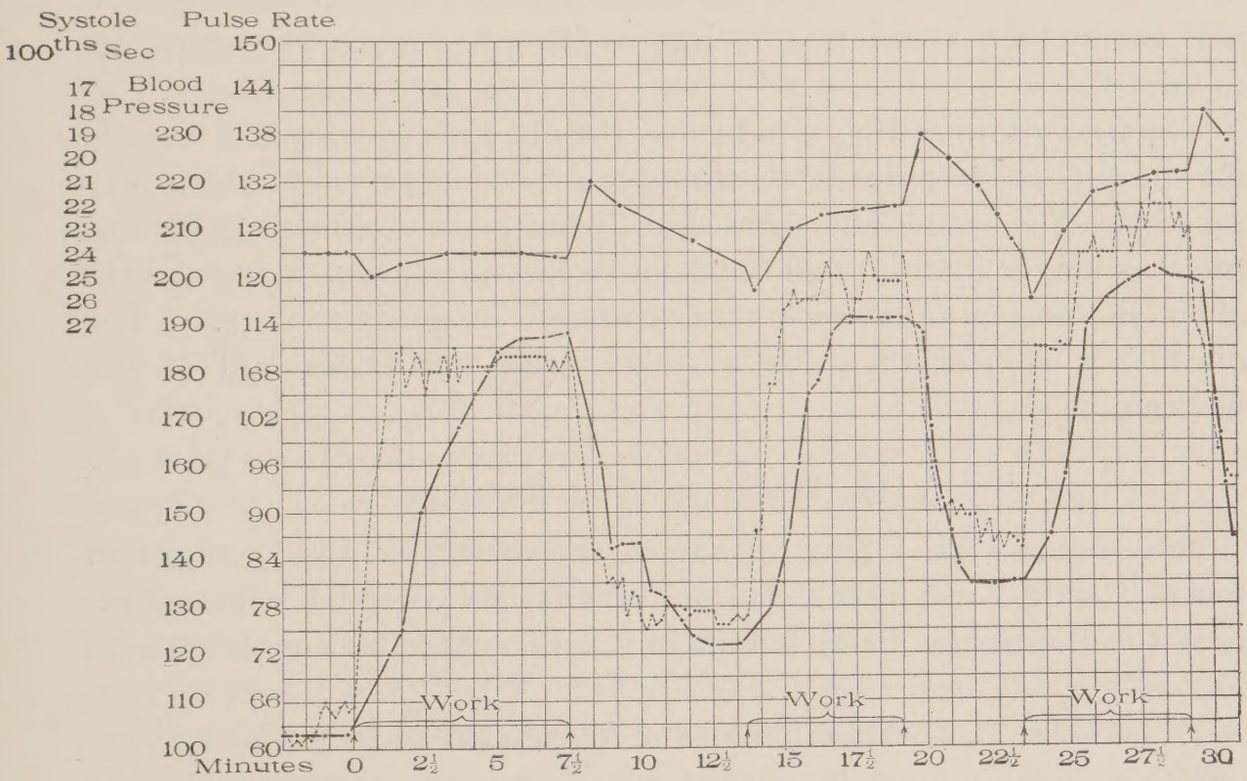

Figure 3. — Changes in pulse-rate, blood-pressure and duration of systole during three working periods of five to seven minutes, with four to six minutes' rest between. Uppermost curve, duration of systole; middle curve (broken line), pulse-rate; lowest curve, blood-pressure. Arrows indicate times of beginning and stopping. Time in minutes. Experiment made July 25, 1903. Subject and work same as in Fig. 2.

interval between the beats.[1] In the present research the duration of systole was determined at intervals of one minute or less during eighteen working periods of three to five minutes, and was also determined continuously during eight working periods of about one minute each, and during four experiments in which several short periods of work were alternated with short periods of rest. The re-

[1] Bowen: *Loc. cit.*, p. 488.

sults clearly verify the former conclusion, although the lengthening of systole when work begins is not equally great in all subjects.

The lowest curve in Fig. 3 indicates the changes in length of systole during three working periods of several minutes each with about four minutes of rest between. In general the systole is seen to shorten during work and lengthen during the intervals of rest,—in full agreement with the results obtained by others. There is, however, a sudden lengthening immediately after work begins, and a sudden and still greater shortening immediately after work stops, in each instance. The curve also shows that the sudden lengthening of systole is at a time when the blood-pressure is beginning to rise, and the sudden shortening is just as the pressure is beginning its rapid fall.

The heavy line in Fig. 4 indicates the changes in length of systole for the successive pulse-beats through a working period of about fifty seconds. The systole lengthens slightly but plainly when work begins, remains longer than normal for about twenty-five beats, then oscillates about the normal until work ceases, when it instantly shortens. The diastole is shorter than the systole during the latter half of the working period.

VIII. Discussion of Results.

Pulse-rate. — As I have discussed the causes of the changes in pulse-rate at considerable length in another place,[1] I will not repeat the discussion here, but merely summarize the conclusions as follows:

1. The first and most rapid rise of pulse-rate when work begins is due to an inhibition of the normal restraining action of the inhibitory centre by nervous impulses arising in the motor centres of the cerebral cortex and in the sensory nerve-endings of the contracting muscles.

2. The continuation of the rise is probably due to nervous impulses of like origin acting upon the accelerator centre; to heat and waste products developed in the heart; to heat and waste products developed in the working muscles; and to increased blood-supply to the tissues of the heart through the coronary arteries. The latter may come about through dilation of these vessels, or because of increased pressure in the aorta.

3. The plateau frequently observed is due to a continuation of the

[1] Bowen: *Loc. cit.*, p. 475.

causes producing the primary rise, the forces involved having reached an adjustment or equilibrium.

4. The secondary rise is due to some of the above causes not becoming effective before, or to changed conditions in the body that render the causes of the primary rise gradually more effective.

5. The rapidity of the pulse during work is much more dependent upon the rapidity of the muscular movements than upon the amount of resistance that is overcome.

Blood-pressure. — When one begins to drive the bicycle there are immediately brought into play three causes tending to raise the blood-pressure: (1) increased pulse-rate, as illustrated by the curve of Fig. 2; (2) contraction of the abdominal muscles, which is shown by a change in the respiratory curves, as well as by the fact that there is conscious effort on the part of the subject; and (3) alternate contraction and relaxation of the large muscle groups of the lower limbs, — the latter two causes hastening the return of the venous blood and thus increasing the pulse-volume.

During the progress of the work at least two influences come into play which tend to lower the blood-pressure: (1) dilation of vessels in the working muscles, which has been demonstrated by Chauveau and Kaufmann,[1] Athanasiu and Carvallo,[2] and others; and (2) dilation of vessels in the skin by the agency of the nervous mechanism regulating body-temperature.[3]

Of these two opposing groups of forces, those tending to raise the pressure become effective first and most abruptly; as a consequence, the first effect of the work upon blood-pressure is a rapid rise. But the forces of the second group keep on increasing, — especially the dilation of skin vessels, which probably does not reach its maximum until profuse sweating occurs, from five to ten minutes after starting. Hence the rapidity of the rise of pressure is soon checked, then balanced; finally, when the second group of influences becomes the greater, the pressure begins to fall.

Two other possible causes of diminished blood-pressure during work should be considered: (1) general dilation of vessels through the agency of the depressor nerve, and (2) diminution of the quantity, of venous blood because of sweating. As to the depressor nerve, we have no direct physiological evidence of the existence of this nerve

[1] CHAUVEAU and KAUFMANN: See Kaufman: *Loc. cit.*

[2] ATHANASIU and CARVALLO: Archives de physiologie, 1898, p. 351.

[3] SCHÄFER: Text-book of physiology, 1900, i, p. 854.

in man; yet its importance in the dog, cat, rabbit, and other mammals, in the absence of any negative evidence in case of man, points to the strong probability that the nerve exists in man, and that it acts during vigorous work to aid in lowering the blood-pressure, and thus protects the heart from overwork. The blood must lose in volume as a result of sweating, but this is gradual, and may be compensated by constriction of splanchnic vessels, as indicated by recent experiments of Hill.[1] Such compensation, however, may not occur during work, when the splanchnic area is under pressure and the systemic vessels strongly dilated.

The variation in the extent of fall in pressure during work in the different experiments was associated with variation in room-temperature, — the fall of pressure being most marked on the warmer days. This variation in the amount of fall is therefore to be attributed to variation in the amount of dilation of skin-vessels. The same variation was observed by Masing, who reports a fall of pressure during work when profuse sweating is present, — not otherwise.[2] This result points clearly to the advantage of "warming up" before attempting to do one's best, as the lowered peripheral resistance lessens the strain on the heart. The advantage of warm weather for athletic competitions is indicated for the same reason.

The more gradual rise of blood-pressure in these experiments, as compared with McCurdy's, can be explained by the different character of the work. It should be borne in mind that this research is a study of the effects of moderate work, such as can be done with safety by the average man; while in McCurdy's, maximal effort was investigated. In the lifting, a greater compression of the splanchnic area results in greater pulse-volume; in the bicycling, the more rapid movements produce a more rapid pulse-rate; both tend to raise the pressure. The difference in the result arises from the difference in the effect of the two kinds of work on the peripheral resistance. In the lifting, the violent and sustained contraction of the muscles nearly obliterates the lumen of the vessels, increasing the peripheral resistance enormously; in the bicycling, the alternate contraction and relaxation of the muscles lessens the peripheral resistance because of the pumping action of the movements on the veins. In lifting, the increased pulse-volume drives the blood-pressure to a great height quickly, because the blood already in the arteries is pre-

[1] HILL: Journal of physiology, 1903, xxviii, p. 122.

[2] MASING: *Loc. cit.*

vented from escaping; in bicycling, the faster pulse-rate can force the pressure up but slowly, because of the comparatively open outlet through the capillaries and veins. It seems to me unnecessary to conclude, with Moritz,[1] that there is a direct psychic cause of the rise in pressure in such cases.

On cessation of work, the forces causing the rise of pressure stop as suddenly as they began at the start, while there is delay in the subsidence of those forces which tend to cause the blood-pressure to fall. The peripheral resistance being less than at the start, the pressure falls more rapidly than it rose. Profuse sweating and the associated dilation of skin vessels continues until the body temperature, somewhat elevated by the work, begins to subside, — frequently eight or ten minutes after stopping. Meanwhile the pressure has fallen below the normal level, and now slowly rises as the vessels constrict.

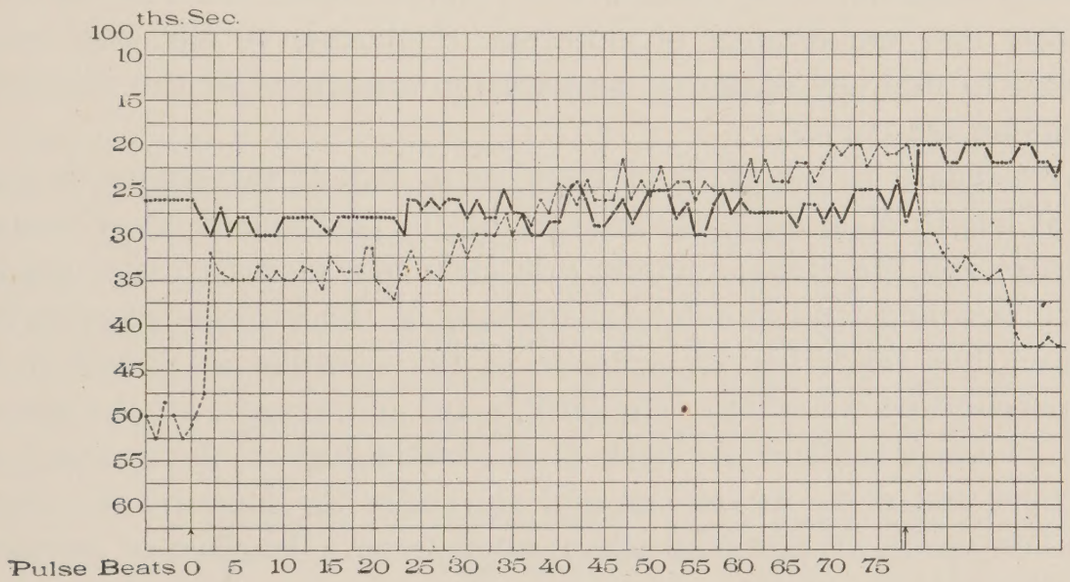

FIGURE 4.—Duration of systole and of diastole during a working period of fifty seconds. Heavy line, duration of systole; light line, duration of diastole. Ordinates indicate duration in 100ths of a second; each unit of abscissa represents one pulse beat; arrows indicate time of beginning and stopping. Experiment made April 17, 1903. Subject, B.; work, about 750 kilogram-metres per minute.

The duration of systole. — In accordance with the results obtained by Edgren, Chapman, and others, we are taught that the systole always shortens as the cycle shortens, and always lengthens as the cycle lengthens.[2] When, therefore, my records indicated a lengthened systole at the beginning of work, while the cycle was

[1] MORITZ: *Loc. cit.*

[2] CURTIS: American text-book of physiology, 1897, i, p. 124.

rapidly shortening, I was inclined to consider the result apparent rather than real, and tried to account for the unexpected result in the following ways:

1. As an error of observation in reading the records.

2. As a failure of the tambour to record the pulse-waves correctly, because of its having a vibration period of its own.

3. As a failure to record the pulse correctly because of changes of air-pressure within the tambour system, due to contraction of muscles of the neck.

4. As a possible effect of changes in blood-pressure upon the times of opening and closing of the aortic valves, and consequent change in the apparent length of systole.

After many careful tests of the apparatus, and after observing the same results in nearly one hundred experiments on about thirty different subjects, using tambours of different sizes, levers of various lengths, and membranes of different thickness, it has not been possible to find any reason to suspect the apparatus or the methods of reading the curves.

With regard to the effect of changes in blood-pressure on the apparent length of systole, as indicated by the positions of the primary upstroke and the dicrotic notch, it is clear that increased pressure in the aorta would tend to delay the opening of the valve and hasten its closure, thus rendering our measure of the duration of systole from the pulse-curve too short; similarly, a fall of pressure in the aorta, such as takes place when work stops, would hasten the opening of the valve and delay its closure, and so render the measure too long. In other words, at the time when we observe a lengthened systole, the change in blood-pressure, by its influence on the time of opening and closing of the semilunar valves, tends to make the systole appear shorter than it really is; and when the shortened systole is observed, the blood-pressure is acting to make it appear longer than it really is. The effect of these changes in blood-pressure is thus seen to minimize the real change in duration of systole rather than to account for it.

It should also be taken into account that determination of duration of systole during muscular work was not attempted by former writers, and therefore a change of systole and cycle in opposite directions is not a contradiction of former results, but an observation in a new field.

Taking all into consideration, it seems reasonable to conclude that

the changes in question are real rather than apparent, and the following explanation is offered to account for them:

Soon after work begins we have an increased blood-pressure and an increased pulse-volume. The heart, being obliged to pump an increased volume of blood against an increased resistance before it has been stimulated to stronger action by the accelerator nerves or by increased blood-supply to its tissues, is not able to empty itself as quickly as before. When work ends, the pressure falls, and the heart, having been stimulated to vigorous action, is able to empty itself more quickly than before. A simple pumping engine slows when it meets increased resistance, and quickens when the resistance is lowered. The heart, being primarily a simple pumping engine, behaves in the same way when it suddenly meets a change in resistance, until its complex regulating mechanism can adjust itself to the new conditions and again assume control.

IX. Practical Bearing of Results.

The practical value of the results of studies in this field depends upon their bearing upon the intensely practical problem of heart-strain. As Roy and Adami have said, "Athletic training is mainly a matter of heart training."[1] We can never lay down proper rules for the guidance of such training until we can determine the changes in heart-strain through a period of vigorous work and the period of recovery from it, since it is through heart-strain that the work most frequently results in injury.

What do we mean by the *heart-strain?* The blood, like all fluids, transmits pressure equally in all directions. During the portion of the cycle when the blood-pressure is at its maximum, the arteries and ventricle are in open communication. It follows that the pressure read upon the sphygmomanometer is not only the pressure in the arteries, but also the pressure exerted by the blood upon each unit of the inner surface of the ventricle. The total amount of pressure thus exerted on the inner surface of the cavity constitutes the *heart-strain*, and is numerically equal to the product of the blood-pressure by the area of the inner surface of the ventricle. The heart-strain varies, therefore, directly with the blood-pressure and with the amount of dilation of the cavity. When from any cause the strain

[1] Roy and Adami: Philosophical transactions of the Royal Society, 1892, B, p. 279.

becomes greater than the heart is able to withstand, the result is either, (1) a stretching of the tissue of the heart-walls, so that the dilation does not pass off when the strain lessens (pathological dilatation), or (2) an enlargement of the orifice between the auricle and ventricle, so that the valve cannot close it completely. (Functional incompetence of the valve.) Both these results may occur at once, and in cases of diseased heart-tissue rupture of the wall sometimes takes place. In thus defining the terms used, reference has been made to the left side of the heart, but the principle is equally applicable to the right side.

It must not be inferred that dilation of the heart is essentially an evil. As pointed out by Roy and Adami, the heart tends to dilate whenever its work is increased, as a matter of economy. The economy results, (1) from the fact that any muscle works at an advantage when somewhat elongated, and (2) because the volume of a spherical mass changes faster than its surface, from which it follows that as the heart dilates, the volume of blood pumped out by a certain linear contraction of the heart-muscle increases faster than the strain. It is only when the dilation becomes excessive, in connection with greatly increased blood-pressure, that harm results.

The relation of heart-*rate* to heart-*strain* is evidently an indirect one, influencing it only as it influences the height of blood-pressure and the amount of dilation. As the blood-pressure can be determined directly, we need only to consider the bearing of heart-rate upon dilation. Now the faster the heart beats, the less is the tendency to dilation; because (1) by pumping faster it does not need to pump so much blood at each stroke, (2) the nervous regulation causing increased rate causes at the same time increased tone of the heart-muscle, and (3) during muscular work the increased rate is associated with increased force of contraction, favoring more complete emptying. Heitler has observed, in case of the dog, that in general an increased heart-rate is associated with a diminished volume, and a lessened rate with enlargement.[1] We have no evidence, therefore, that a rapid pulse-rate during work is of itself a direct source of danger; it is apparently a protection against overfilling of the cavities and consequent increase of strain.

When work begins, the heart-strain must increase rapidly, because of the great increase in blood-pressure; the fall of pressure during work must tend to relieve it. We cannot tell when the heart-strain

[1] HEITLER: Centralblatt für innere Medicin, 1903, p. 625.

is greatest, because the amount of dilation is one of the two factors, and this is at present an unknown quantity. We have an increase in pulse-volume, amount unknown, tending to increase the dilation; an increased rate of beat, tending to prevent it; and fatigue, another unknown factor, tending to increase it. Roy and Adami[1] go so far as to say that fatigue and dilation of the heart may be considered as synonymous terms. When work ceases, we have sudden and great changes in rate and pressure, but the amount of dilation is again an unknown factor, and hence the strain cannot be estimated with any certainty. Before the question of heart-strain can be answered we must be able to state what changes occur in the volume of the heart together with the changes in pressure.

Two principal methods of studying the size of the heart are in use: (1), percussion of the chest wall, and (2), the fluoroscope. The former cannot be used with success during work because of the noise involved. The latter method is far superior in exactness under any circumstances. Schott[2] found a considerable dilation of the heart after vigorous work in wrestling, using both methods. Several scientists have improved the methods of using the fluoroscope in such study. Moritz[3] and De La Camp[4] have failed to verify Schott's results in sound men, but the latter found dilation five minutes after work in cases suffering from disease of the heart. He concludes that maximal muscular efforts cause acute dilation of the heart only when the organ is diseased. Neither of these writers attempted to study the size of the heart during the work. It is to be hoped that extensive studies of the amount of dilation during work will soon be carried on, and preferably in connection with determinations of blood-pressure. Such a study should give results enabling us to determine the conditions which cause the greatest heart-strain, and thus help to put athletic training on a new and firm basis, substituting intelligent methods of training for guess work.

X. Summary.

a. By the use of the stationary bicycle the effects of exercises of speed and endurance upon the respiratory and circulatory systems can be studied with accuracy during the progress of the work.

[1] Roy and Adami: *Loc. cit.*, p. 282.
[2] Schott: Medical record, 1898, p. 436.
[3] Moritz: Münchener medicinische Wochenschrift, 1902, p. 1.
[4] De La Camp: Zeitschrift für klinsche Medicin, 1903, li, p. 1.

b. During moderate exercises of speed the following changes take place in the circulatory system :

1. A rapid primary rise of pulse-rate when work begins, lasting from one to three minutes; a gradual secondary rise as the work continues, often separated from the primary rise by a plateau; a rapid primary fall when the work stops, followed by a more gradual secondary fall, the two also being separated by a plateau in some instances.

2. A rapid rise of blood-pressure when the work begins, lasting from five to ten minutes; a gradual fall of pressure as the work continues; a rapid fall to normal or subnormal when work stops.

3. A sudden lengthening of systole when work begins; a gradual shortening as the work continues; a sudden and pronounced shortening when work stops, followed by a gradual lengthening to normal.

c. The following explanations are offered to account for these changes:

1. The first changes in pulse-rate when work begins and when it stops are due to nervous impulses acting upon the inhibitory centre. Nervous impulses acting upon the accelerator centre and effects of heat and waste products come in later.

2. The rise of blood-pressure when work begins is produced by increased pulse-rate, contraction of abdominal muscles, and pumping action of the working muscles upon the veins; the latter two causes hastening the return of venous blood and thus increasing the pulse-volume.

3. The cessation of the rise of pressure during work, while the pulse-rate is still rising, is due to diminished peripheral resistance, because of dilation of vessels in the working muscles and in the skin; possibly also aided by the action of the depressor nerve and diminution of blood-volume by sweating.

4. The extent of the fall of pressure during work depends upon the extent to which the skin-vessels are dilated, which in turn depends upon the temperature of the air and amount of clothing worn by the subject.

5. The sudden changes in systole at the beginning and end of work are due to sudden changes in the work of the heart before the regulating mechanism has time to adjust itself to the changed conditions.

d. The practical bearing of these results on the ultimate problem of heart-strain is as follows :

1. A rapid pulse is never an immediate cause of heart-strain, nor a safe indication of how great a strain is present.

2. The changes in blood-pressure during work influence the amount of strain on the heart directly and proportionally, but the time of greatest strain and the general changes in amount of strain cannot be determined without a parallel determination of blood-pressure and change in heart-volume.

3. The maximum heart-strain produced by a certain amount of work is diminished by gradually "warming up" before doing the most vigorous part of it, and is also less when the temperature is warm.

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